Reliability of Ground Reaction Forces During a Vertical Jump: Implications for Functional Strength Assessment

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Objective: To determine the reliability of ground reaction force during a vertical jump.

Design and Setting: Two test sessions 48 hours apart in which subjects performed five maximal vertical jumps with their right lower extremity on a force platform without arm movement. Applied Biomechanics Laboratory at the University of Toledo.

Subjects: Nineteen healthy males (n = 12) and females (n = 7), with an average age of 21.3 years and 23.2 years, respectively, from the University of Toledo participated in this study. The average height for males and females was 70.0 and 66.6 inches, respectively. The average weight for males was 170.5 lbs., while the average weight for females was 132.4 lbs.

Measurements: Reliability of the peak vertical ground reaction force and vertical impulse was assessed using the formula for intraclass correlation coefficient (2,1) (ICC [2,1]).

Results: Measurement of peak vertical ground reaction force was demonstrated to be very reliable (ICC [2,1] r_{xx} = .94; SEM = .003% BW), whereas the reliability estimate for vertical impulse was not very reliable (ICC [2,1] r_{xx} = .22; SEM = .24% BW seconds). Furthermore, no significant relationship was found between peak vertical ground reaction force and vertical impulse. (BW = body weight; SEM = standard error of measurement).

Conclusions: We conclude that peak force measured during a one-legged vertical jump is reliable and may provide an alternate method of evaluation of lower extremity functional strength.

Key Words: ground reaction forces, vertical jump, functional strength assessment, closed kinetic chain

A common issue in rehabilitation involves the determination of an individual's readiness for return to normal levels of activity. This is particularly problematic in dealing with athletes, since their normal level of activity may involve musculoskeletal stress that far exceeds that of a nonathletic population. Often subsequent injury occurs when athletes are returned to competition too early, which may result from inaccuracies in the assessment of their functional abilities. To resolve this problem, clinicians have recently begun to emphasize the use of functional testing following rehabilitation.[14,15,20,25] In contrast to more traditional methods of assessment that focus on isolated joint testing, functional testing involves the evaluation of complete skills necessary for complex sport activities. It is felt that such assessment may be more relevant to the ability of athletes to perform these skills in the context of their specific sport.[3,14,15,17,19] As such, functional testing may provide a better estimate of the athlete's true readiness for return to activity.

Much of the present research regarding lower extremity assessment has focused on quantifying functional agility,[14,15,20,25] while little data exists on the topic of functional strength.[5,16] In some studies,[16,23] the expression "functional strength" has been associated with lower extremity strength training, yet it has not been clearly delineated. Although assessing functional strength is important following rehabilitation, it is necessary to first develop a construct for defining functional strength. Conceivably, a logical definition of functional strength is "the force produced by the lower extremity in a movement specific to sport," where most sport activities involve the lower extremity positioned in a closed kinetic chain.[3,17] However, both functional agility and functional strength assessment are important for the total rehabilitation of athletes when considering their return to competition.

Since many sports involve jumping movements or similar activities dependent on the generation of lower extremity power,[10,18] the vertical jump appears to provide a useful means of estimating lower extremity functional strength. Vertical jump performance is a well-documented measure of human power.[2,11,21] Peak force produced during a one-legged vertical jump correlates highly with peak power and vertical jump height attained.[4,6] Generation of peak force results from the net muscle moments created by the knee and hip extensors and ankle plantarflexors during propulsion. Another variable useful in evaluating lower extremity strength is vertical impulse. Vertical impulse represents the product of force and time during the propulsion phase of the jump. Essentially, vertical impulse is an accelerating force where a change in momentum occurs on the body.[13]

Directly measuring peak vertical ground reaction force and vertical impulse during the propulsion phase of a one-legged vertical jump may provide a valid means for quantifying estimates of lower extremity functional strength. However, as with all evaluation techniques and protocols, functional testing is very much dependent on the reliability of the test.[24] Unfortunately, no data exist concerning the reliability of peak vertical ground reaction force and vertical impulse produced

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during a functional task. Since the one-legged vertical jump appears to be a relevant test of functional strength, and analyzing ground reaction forces from the test provides insight into lower extremity force production, assessing the reliability of peak vertical ground reaction force and vertical impulse emerges as necessary. Thus, the purposes of this investigation were: 1) to determine the test-retest reliability of peak vertical ground reaction force and vertical impulse created during a one-legged vertical jump; and 2) to determine the relationship between peak vertical ground reaction force and vertical impulse produced during a one-legged vertical jump.

METHODS

Nineteen healthy student volunteers participated in the study. Subject characteristics are presented in Table 1. The investigator ensured that each subject read and signed an informed consent form approved by the University of Toledo's Human Subjects Research Review Committee. Participants reported no previous lower extremity injury, orthopaedic abnormalities, vestibular problems, or vision problems. All were familiarized with the purpose of the study and testing procedures.

One-Legged Vertical Jump Protocol

All participants performed the one-legged vertical jump protocol using the right lower extremity. Subjects reported to the laboratory on three separate occasions. The first meeting consisted of an orientation session in which the investigator instructed the subjects on the proper technique of the jump and the subjects performed multiple trials until they felt comfortable with the established jump protocol. They were then required to come in the next day for the first test session. At the beginning of the first test session subjects placed their right foot on the middle of the force plate, with their contralateral knee flexed at 90° to prevent the left foot from touching the force platform. They began each jump from an upright position. The protocol allowed for countermovement, although arm movement during the jump was restricted by having subjects cross their arms against their chests.[5] Arm swing used during the vertical jump has been shown to increase peak force compared to jumps performed without arm movement;[11,21] thus, we wanted to evaluate force production consequent to lower extremity strength only. We instructed the subjects not to go past 90° of knee flexion with the right extremity during this countermovement. Once the subject was set on the force platform, the investigator gave the command "go," which initiated the subject's jump. Each subject had 5 seconds to complete the jump. Subjects rested 1 minute between trials and were encouraged to jump maximally on each trial. The second series of testing occurred 48 hours later under the same testing procedures.

Table 1. Description of Subject Characteristics (Mean ± SD)

	Age (yr)	Height (in)	Weight (lb)
Males (n = 12)	21.3 ± 4.6	70.0 ± 2.3	170.5 ± 28.7
Females (n = 7)	23.2 ± 5.3	66.6 ± 4.3	132.4 ± 25.9

Data Collection

Subjects performed one-legged vertical jumps on a force platform (AMTI, model OR5-1; Newton, MA). The force platform was interfaced through a 12-bit analog-to-digital converter (Data Translations Inc, model DT2,801; Marlborough, MA) to a PC Brand 386 microcomputer. The raw force data were sampled at 200 Hz and digitally filtered with a second-order, low-pass Butterworth digital filter with the cut-off frequency set at 6 Hz. The program sampled the vertical ground reaction force data for each trial for a 5-second period. Customized software was used to perform an ensemble average of the 5 test trials for each subject from session 1 and session 2. The average peak vertical ground reaction force and vertical impulse for each subject from session 1 and session 2 were used for analysis.

Statistical Analysis

To estimate the reliability of peak vertical ground reaction force and vertical impulse the intraclass correlation coefficient (2,1) (ICC [2,1]) as described by Shrout and Fleiss[22] was used. The ICC (2,1) was chosen as the reliability estimate since it provides an estimate that includes the variability of measurements taken by any investigator on any subject.[22] The ICC (2,1) is represented by the following equation:[22] ICC $(2,1) = (BMS-EMS)/\{BMS + (k-1)EMS + [k(JMS\text{-}EMS)/n]\}$, where BMS = between mean square, EMS = residual mean square, JMS = between judges mean square, k = the number of sets of scores, and n = the number of persons observed. Mean square terms were acquired using the univariate F-statistic within the reliability statistics using SPSS for Windows v6.1 software (SPSS Inc, Chicago, IL). The standard error of measurement (SEM) was calculated as described by Gullickson.[9] It evaluates the difference between a subject's true score and observed score for a given test. A Pearson-product moment correlation was calculated between average peak vertical ground reaction force and average vertical impulse to determine the relationship between these two kinetic parameters. The level of significance was set a priori at $p < .05$.

RESULTS

In Table 2 the means and standard deviations are shown, as well as the reliability data for peak vertical ground reaction force and vertical impulse for each test session. The coefficient of stability estimate calculated for peak vertical ground reaction force was considered high ($r_{xx} = .94$), whereas for vertical impulse, a low reliability estimate ($r_{xx} = .22$) was discovered. No significant correlation ($p > .05$) was found between peak vertical ground reaction force and vertical impulse for test 1 ($r_{xy} = -.21$) and test 2 ($r_{xy} = -.28$). These values can be seen in Table 3.

Table 2. Descriptive Statistics (Mean ± SD) and Reliability Information for Ground Reaction Force Parameters for Test 1 and Test 2

Variable	Test 1	Test 2	ICC*	SEM†
PVGRF (%BW)‡	1.90 ± .23	1.92 ± .26	.94	.003
Min	1.62	1.60		
Max	2.51	2.45		
VI (%BW sec)§	1.30 ± .50	.91 ± .22	.22	.24
Min	.77	.10		
Max	2.30	1.16		

* ICC, intraclass correlation coefficient.
† SEM, standard error of measurement.
‡ PVGRF, peak vertical ground reaction force; BW, body weight.
§ VI, vertical impulse.

Table 3. Correlation Coefficients of Peak Vertical Ground Reaction Force and Vertical Impulse for Test Session 1 to Test Session 2

	$PVGRF_1$†	$PVGRF_2$
VI_1‡	−.21*	−.19*
VI_2	−.28*	−.27

† PVGRF, peak vertical ground reaction force.
‡ VI, vertical impulse.
* These correlations are not significant ($p > .05$).

DISCUSSION

In the most applied sense, the main objective of the vertical jump is to achieve maximum vertical height. To obtain maximum vertical height, the body's center of gravity needs to be as high above the ground as possible, with the greatest vertical velocity at the instant of take-off.[6,11] Sequential segmental rotations act to move the body's center of gravity, vertically, in a rectilinear path.[13] These segmental rotations result in external forces, or ground reaction forces, that are created as the jumper pushes against the ground to overcome inertia in accelerating the body upward. Due to Newton's second law, vertical displacement of the body's center of gravity can be influenced by manipulating the components of the vertical ground reaction force. Thus, evaluation of these components provides insight into the strategy that the individual has employed to maximize vertical jump height.

No previous literature was found reporting reliability estimates for peak vertical ground reaction force and vertical impulse produced during a one-legged vertical jump. The high test-retest reliability of the peak vertical ground reaction force obtained in this study ($r_{xx} = .94$) indicates that this measurement is stable over time. These results are consistent with those from a similar study[11] involving a two-legged vertical jump in which the reliability of peak vertical ground reaction force was reported to be .97. The high coefficient of stability for peak vertical ground reaction force found in this study indicates that maximal force produced by the leg extensor and ankle plantarflexor muscles during the jump is reproducible.

Quantifying the peak force generated during the vertical jump has important clinical implications: it may be an accurate and appropriate measure of one's ability to generate lower extremity power. It also allows the clinician to assess an athlete's lower extremity strength during a functional movement. This is significant because it considers the muscular force produced by the lower extremity in a weight-bearing closed kinetic chain environment. Furthermore, since peak force produced during a one-legged jump yields consistent results, the relative contribution of the noninvolved limb can be controlled. Additionally, a significant and high relationship has been demonstrated between peak vertical force produced and jump height achieved.[4,6] This suggests that peak vertical ground reaction force is a good indicator of lower extremity muscle strength and strongly predicts functional performance. Furthermore, peak force measured during a one-legged vertical jump appears to be more functional and sport-specific than traditional open kinetic chain testing procedures.

It may be argued that we should have measured pure vertical jump height from a simple jump and reach test. The problem with this measurement is that arm movement significantly increases peak force production, and, ultimately, greater jump height is attained during the jump.[21] As a result, arm movement masks the segmental torque production created by the lower extremity musculature during the jump-and-reach test. However, if vertical jump height achieved is of interest to the clinician, it can be calculated more accurately, from the kinetic and temporal variables produced by the force-time curves, by analyzing the ground reaction forces.[6]

The relationship between impulse and momentum is quite interesting when considering vertical jump performance. The impulse-momentum relationship exists because the product of the applied force and time (impulse) determines the change of momentum an object possesses. Momentum is simply the product of a given mass and its velocity.[13] If a change in momentum is to occur, an impulse must be applied. With respect to the force-time curve, impulse is characterized as the area under the curve. This area can easily be determined by multiplying the magnitude of force by the duration of time occurring at each point throughout the curve. Because vertical impulse is a function of force and time, it represents the interaction between force generated and time during the jump.[7] A change in vertical impulse is therefore dependent on changes in either force or time.

Since the purpose of pushing-type activities is to cause an increase in the velocity of a body or object, the time in which the applied force is acting should be maximized.[13] In terms of vertical jump activity, a compromise between the development of maximal force and maximal time of force production needs to exist. Vertical jump performance can suffer if the subject fails to maximize leg extension acceleration or propulsion time in generating the impulse during the jump. Basically, providing more time for the force to accelerate the body during the jump enables more time for the applied force to create a greater take-off velocity.[13] Dowling and Vamos[6] evaluated the importance of vertical velocity produced at take-off and its contribution to vertical height attained. They found that subjects who acquired the greatest jump height achieved the greatest vertical velocity at take-off, which resulted from a greater vertical impulse. Knowledge of the vertical impulse in relation to peak force production is critical for the sports therapist in evaluating an athlete's functional strength because it can then be known if a deficit exists in either the force or time of force production.

Although maximum force development is critical, the time in which the individual generates the force must be considered.

In this study, there was poor test-retest reliability for vertical impulse, unlike the results reported by Harman et al.[11] As previously indicated, their subjects performed two-legged jumps, which may be associated with enhanced balance and motor control during the jump. This may have positively affected the consistency of the involved movement patterns, which would be reflected in the reliability scores. In the present study, we found measurement of peak vertical ground reaction force to be highly reliable. As a result, it appears that time was the factor being manipulated, thus leading to the poor reliability for vertical impulse. In other words, subjects were able to produce consistent peak force output of the leg extensor musculature; however, the duration of this force changed. Perhaps, the poor reliability estimate found for vertical impulse was due to the unique neuromuscular strategies involved in performing a one-legged vertical jump.[8] In a simulation study[1] evaluating the effects of muscle strengthening on vertical jump height, it was found that increasing muscle strength while ignoring control mechanisms of the jump led to a decrease in jump height. In considering one-legged vertical jump performance, balance may be an important neural component to train. These strategies may be better explained and further explored with electromyography.

In examining the correlation coefficients between peak vertical ground reaction and vertical impulse in test 1 and between peak vertical ground reaction force and vertical impulse in test 2 (Table 3), a nonsignificant relationship was found. This result can be explained by the fact that the measurement of vertical impulse proved to be very unreliable. Additionally, the moderate sample size used in the study may have contributed to poor statistical power and thus a nonsignificant relationship. Based on the magnitude of the correlation coefficients found between peak vertical ground reaction force and vertical impulse in test 1 (-.21) and between peak vertical ground reaction force and vertical impulse in test 2 (-.28), sample sizes of 92 and 47, respectively, would have yielded a significant relationship with the probability set at .05 for a two-tailed test.[12] It should be remembered that sample size affects not the magnitude of the relationship but rather the accuracy of the relationship.[12] Further research should be done to explore the relationship of these variables in attempting to evaluate lower extremity functional strength using this protocol.

In conclusion, measurement of peak vertical ground reaction force during a one-legged vertical jump is reliable and allows the clinician to evaluate lower extremity strength during a sport-specific movement. Force platform dynamometry provides an alternative and accurate way to evaluate lower extremity force in estimating closed kinetic chain strength. Additional research needs to be done using the above-mentioned protocol to establish the sensitivity and validity of measurements comparing force production in injured and noninjured extremities.

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